A Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures
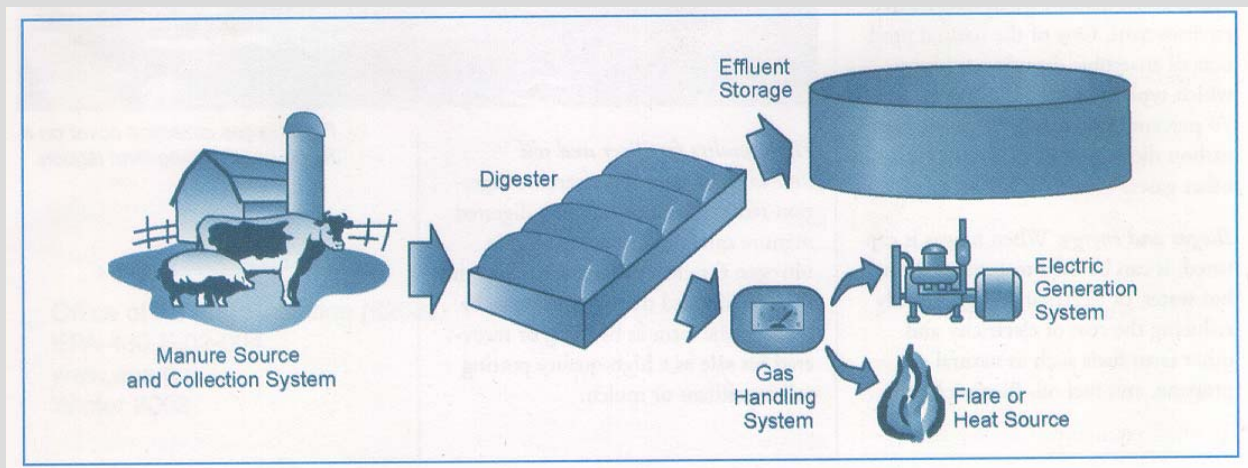
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ENERGY AND POLLUTION PREVENTION

In Memory of

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Acknowledgments

Contents

Introduction

Anaerobic digestion of livestock manures under controlled conditions to produce biogas (a mixture of methane and carbon dioxide) can provide livestock producers with the opportunity to increase net farm income, typically by using captured biogas to generate electricity for on-site use, or delivery to a local electric utility, or both. This biogas utilization approach also provides an opportunity to utilize waste heat captured from an engine-generator set to reduce on-farm demand for conventional fuels (*e.g.*, fuel oil and propane) that are often used for water and space heating. Direct combustion of biogas for on-farm water and space heating is also an option. An added benefit of anaerobic digestion of livestock manures is that potentially negative impacts of these wastes on air and water quality are reduced. This includes, but is not limited to, reducing emissions of methane, a greenhouse gas with approximately 21 times the heat-trapping capacity of carbon dioxide. Methane emissions occur when manure decomposes anaerobically under uncontrolled conditions. Producing, capturing, and using manurial biogas as a fuel reduces emissions of carbon dioxide from fossil fuel combustion to generate electricity or produce heat. -

Recent construction of a number of successful systems and an increased awareness of the benefits of manurial biogas (production and utilization) has produced an increased level of interest by livestock producers. Concurrently, as the number of system developers increased, a number of different system design approaches have emerged with claims about performance superiority. In some instances, these claims are supported by results of rigorous performance evaluations, whereas others are based on minimal data.

This protocol was developed with the objectives of providing:

1. System developers with a standard approach for quantifying the performance of their systems and supporting claims that will receive general acceptance as credible, and
2. Third parties with the same approach for independent performance evaluations.

Adherence to this protocol will allow for comparisons of similar and different types of systems based on directly comparable and unbiased information. This protocol also establishes the standard for acceptance of performance evaluation reports in a central repository for easy access

by interested parties and possibly for a design certification program in the near future. At this time, options for establishing and supporting a repository, which most probably will be a web site, and a certification program, are being evaluated.

This protocol specifies prerequisites for performance evaluations and assembly of appropriate background information. It also describes acceptable methods for data collection to characterize system performance with respect to waste stabilization and biogas production and utilization. Additionally, a uniform approach for evaluating economic viability is established.

Prerequisites for Performance Evaluations

The following are prerequisites for evaluations of performance of manurial biogas systems. All performance evaluations should be:

1. Conducted on full-scale systems serving commercial livestock operations,
2. At least 12-months in duration, and
3. Conducted only after the start-up phase of operation has been completed and the following conditions are met:
    a. Plug-flow and mixed digesters—Continuous operation for a period equal to the sum of at least five hydraulic retention times (HRTs) after startup phase completion.
    b. Covered lagoons—Continuous operation for at least one year after startup.
    c. Attached film digesters—Continuous operation for at least three months after startup with the three months of operation occurring during warm weather for unheated digesters.

Background Information

The importance of compiling and reporting adequate background information, as part of manurial biogas system performance evaluations, cannot be over emphasized. Such information is critical for evaluating reported results in the proper context. Below are lists of the information on the livestock operation (Table 1) and the biogas production and utilization system (Table 2) that should be assembled and included in all performance evaluation reports. If the performance evaluation is of a centralized system, the information specified in Table 1 should be provided for each livestock operation served.

Process Performance Characterization

Waste Stabilization Parameters

All evaluations of the performance of manurial biogas production and utilization systems should include the quantification of the degree of waste stabilization being realized by the anaerobic digestion process. For mixed, plug-flow, and attached film digesters, the degree of waste stabilization claimed should be based on differences, when statistically significant, among mean influent and effluent concentrations of total solids (TS), total volatile solids (TVS), chemical oxygen demand (COD), and total volatile acids (TVA). In addition, it must be demonstrated that the observed changes in concentrations of these parameters are due to microbial processes and not settling of particulate matter by showing that that there is no statistically significant difference ($P<0.05$) between influent and effluent fixed solids and preferably also total phosphorus (TP) concentrations. Ideally, changes in concentrations of total Kjeldahl nitrogen (TKN), organic nitrogen (ON), ammonia nitrogen (NH_4-N), TP, and total sulfur (S) also should be determined. Mean influent and effluent pH values should also be accounted for in conjunction with the other parameters listed above.

Table 1. General Information about Livestock Operations.

1. Name of operation

2. Address (including county)

3. Type of operation (*e.g.,* dairy, swine, layer, *etc.*)

4. If dairy,
   a. Breed (*e.g.,* Holstein, Guernsey, *etc.*)
   b. Average number of lactating cows
   c. Average number of dry cows
   d. Average number of replacements
   e. Respective fraction of the manure from the milking herd, dry cows, and replacements collected for digestion
   f. Type(s) of manure collection system (*e.g.,* scrape, flush, *etc.*) and frequency of manure collection

5. If swine,
   a. Type of swine operation (*e.g.,* farrow-to-wean, farrow plus nursery, farrow-to-finish, *etc.*)
   b. Average number of sows and pregnant gilts and number of litters per sow-year
   c. Average number of nursery pigs and number of nursery stage cycles per year
   d. Average number of feeder pigs and number of grow/finish cycles per year
   e. Type(s) of manure collection systems (*e.g.,* flush, pull-plug pit, *etc.*) and frequency of manure collection

6. If layer,
   a. Average number of hens
   b. Type of manure collection system (*e.g.,* scrape, flush or pull-plug pit) and frequency of manure collection

7. For animal operations other than those listed above,
   a. Numbers and ages of animals
   b. Type of manure collection system

Table 2. Biogas System Information.

Biogas Production

1. Type of digester (*e.g.,* mixed, plug-flow, attached film, or covered lagoon)

2. Name of system designer, address, and other contact information

3. Digester design assumptions

    a. Number and type of animals
    b. For lactating cows, average live weight or average milk production
    c. For swine, type or types (*e.g.,* gestating sows, lactating sows, feeder pigs, *etc.*) and average live weight
    d. Bedding type and estimated annual quantity used
    e. Manure volume, ft^3/day (m^3/day)
    f. Wastewater volume, ft^3/day (m^3/day) (*e.g.,* none, milking center wastewater, confinement facility wash-down, *etc.*)
    g. Other waste volume(s), ft^3/day (m^3/day) (*e.g.,* none, food processing wastes, *etc.*) with physical and chemical characteristics (*e.g.,* concentrations of total solids, total volatile solids, chemical oxygen demand, *etc.*)
    h. Pretreatment before digestion (*e.g.,* none, gravity settling, stationary screen, screw press, *etc.*)
    i. Treatment of digester effluent (*e.g.,* none, solids separation by screening, *etc.* with details including use or method of disposal)
    j. Method of digester effluent storage (*e.g.,* none, earthen pond, *etc.*)

4. Physical description

    a. General description including types of construction materials (*e.g.,* partially below grade, concrete channel plug-flow with flexible cover, *etc.*)
    b. Dimensions (length and width or diameter and height or depth)
    c. Type(s), location(s), and thickness(s) of insulation
    d. Operating volume and ancillary biogas storage volume if present
    e. Design hydraulic retention time
    f. Design operating temperature
    g. Compliance (yes or no) with the applicable Natural Resources Conservation Service Conservation Practice Standard (No. 365: Anaerobic Digester—Ambient Temperature or No. 366: Anaerobic Digester—Controlled Temperature)

Table 2. Continued.

Biogas Production (continued)

5. Monthly summaries of operational details

    a. Number and type of animals
    b. Other waste volume(s) and physical and chemical characteristics
    c. Frequency of waste addition (*e.g.,* once per day, twice per day, *etc.*)
    d. Pretreatment of digester influent (*e.g.,* none, solids separation by gravitational settling, screening, *etc.* with details)
    e. Average daily digester temperature and monthly range
    f. Use of monensin or any other antibacterial growth promoters that may affect biogas production

Biogas Utilization

1. Biogas utilization (*e.g.,* none, generation of electricity, use on-site as a boiler or furnace fuel, or sale to a third party)

2. If generation of electricity,

    a. Type of engine-generator set (*e.g.,* internal combustion engine, micro turbine or fuel cell with the name of the manufacturer, model, power output rating (kW or MJ) for biogas, and nominal voltage
    b. Component integration (factory or owner)
    c. Origin of equipment controller (manufacturer integrated, third party off-the-shelf, or third party custom)
    d. System installer
    e. Stand-alone capacity (yes or no)
    f. Pretreatment of biogas (*e.g.,* none, condensate trap, dryer, hydrogen sulfide removal, *etc.* with the names of manufacturers, models, *etc.*)
    g. Exhaust gas emission control (*e.g.,* none, catalytic converter, *etc.*)
    h. If interconnected with an electric utility
        i. Name of the utility
        ii. Type of utility contract (*e.g.,* sell all/buy all, surplus sale, or net metering)
    i. If engine-generator set waste heat utilization
        i. Heat source (*e.g.,* cooling system or exhaust gas or both) and heat recovery capacity (Btu or kJ/hr)
        ii. Waste heat utilization (*e.g.,* digester heating, water heating, space heating, *etc.*)

Table 2. Continued.

Biogas Utilization Continued

3. If use on-site as a boiler or furnace fuel, a description of the boiler or furnace including manufacturer, model, and rated capacity (Btu or kJ/hr)

4. If biogas sale to a third party, a description of the methods of processing, transport, and end use

Cost Information

1. "As built" cost of total system

2. Cost basis (*e.g.,* turnkey by a developer, owner acted as the general contractor, constructed with farm labor, *etc.*)

3. An itemized list of component costs (*e.g.,* the digester, the biogas utilization system, *etc.*)

For covered lagoons, differences between influent and effluent concentrations for those parameters present in both particulate and soluble forms (*e.g.,* TS, TVS, and COD) represent changes due to the combination of microbial processes and settling and are not valid indicators of the degree of waste stabilization being achieved. Although these differences have value in characterizing effluent water pollution potential and should be reported, quantification of the degree of waste stabilization should be based on the difference between influent and effluent TVA concentrations and COD reduction estimated based on methane production. Stoichiometrically, 5.60 ft^3 of methane is produced per lb of COD destroyed (0.3496 m^3 per kg COD destroyed) under standard conditions (0°C and 1 atm) (Madigan *et al*., 1997). The assumed quantity of methane produced per unit COD destroyed under other than standard conditions must be adjusted to actual conditions using the universal gas law (See Metcalf and Eddy, Inc., 2003 and Appendix B). It is recommended that this approach for estimating COD reduction also be used in evaluations of other types of digesters and compared to estimates based on the difference between mean influent and effluent concentrations (See Appendix A for a discussion of the construction of materials balances).

Although methane production also can be expressed as a function of TVS destruction, the nature of this relationship is variable depending on the chemical composition of the TVS destroyed. The variation among different types of livestock manure in chemical composition, as well as the impact of different feeding programs and possibly other variables within the different sectors of animal agriculture, suggests that there is no single, generally applicable conversion factor as with COD. For example, the generally accepted possible degree of variation in total biogas production during the anaerobic digestion of domestic wastewater biosolids can vary from 12 to 18 ft^3 per lb of TVS destroyed (0.7492 to 1.124 m^3 per kg TVS destroyed) (Metcalf and Eddy, Inc., 2003). A defensible basis for estimating TVS destruction during the anaerobic digestion of livestock manures based on methane production at this time seems to be lacking but may emerge in the future.

Finally, it is recommended that long term, bench scale batch studies be conducted at the operating temperature of the digester being evaluated to estimate the readily biodegradable and refractory fractions of TVS. Such studies should be for no less than 30 days and with the refractory fraction at infinity (TVS_∞/TVS_0) determined by plotting TVS_t/TVS_0 versus ($1/TVS_0 * t$), where t equals zero at the beginning of the study and determining the y-axis intercept using linear regression analysis.

Pathogen Reduction

At a minimum, all claims of pathogen reduction potential, should be supported by results of the analyses of the digester or covered lagoon influent and effluent samples collected and analyzed for the waste stabilization parameters previously listed. Claims of pathogen reduction potential may be based solely on reductions in the densities of the total coliform and fecal streptococcus groups of indicator organisms as long as it is clearly explained that reductions in these groups of microorganisms only are indicative of the potential for pathogen reduction. If the demonstration of reduction of a specific pathogen is desired, preference should be given to *Mycobacterium avium paratuberculosis* in dairy manure and *Salmonella spp* in swine and poultry manures.

<u>Sample Collection</u>

Given the inherent variability in animal manures, care should be taken to insure that all influent and effluent samples collected for analysis are representative of the average daily flow. While the most desirable approach would be to collect 24-hour flow composited samples, it is recognized that this approach generally is impractical for collection of livestock manure samples. Thus, the following alternatives are recommended.

1. With influent and effluent lift stations, a series of at least five grab samples should be collected at different depths when the lift station is at maximum capacity and then combined into a single composite sample. When possible, the contents of the lift station should be mixed before sample collection.

2. When samples have to be collected from a continuously or periodically flowing influent or effluent stream, a series of at least six grab samples should be collected over a period of no less than one hour and combined into a single composite sample.

Composite samples should be no less than 20 L (~5 gal) and sub samples withdrawn for analysis should no less than one L (~ one qt). To insure that samples collected are representative, there should be an ongoing review of analytical results to determine if the degree of variability is reasonable or a modification of the sample collecting protocol is necessary.

Because of inherent variability over time, all claims with respect to waste stabilization must be based on the results of the analysis of a minimum of 12 monthly influent and effluent samples with the following caveat. If the coefficient of variation for influent or effluent TS concentrations exceeds 25 percent, or there is more than one extreme observation determined statistically to be an outlier, more frequent sample collection and analysis may be necessary, with at least 24 semi-monthly sampling episodes recommended.

With co-digestion of livestock manure and another waste or combination of other wastes or another feedstock, a sampling plan must be devised that will characterize the digester influent and effluent to accurately delineate the degree of waste stabilization being realized as well as the relationship between waste stabilization and biogas production. If the same waste or

combination of wastes or another feedstock is being combined with manure continually and at a constant rate, periodic sampling as described above should be sufficient. If, however, different wastes are being combined with manures at different times, or co-digestion is intermittent or both, adequate evidence must be provided that the physical and chemical characteristics of the digester influent and effluent reported as mean values are representative.

A complete performance evaluation involving co-digestion should also include a record of all additions of other wastes for a period equal to at least five HRTs prior to and through the 12-month duration of the performance evaluation. This record should be included in the report of the performance evaluation and include at least the following:

1. Type and source of the waste(s) or other feedstocks,
2. Date(s) of addition,
3. Volume added, and
4. TS, TVS, COD, and TVA concentrations and pH using the same analytical protocols being used for determining digester influent and effluent physical and chemical characteristics.

Sample Preservation

All anaerobic digester influent and effluent samples should be immediately iced or refrigerated following collection and delivered within 24 hours of collection for analysis. Given the high concentrations of organic matter, subsamples should not be acidified for preservation. In addition, the necessity of splitting samples and introducing another source of possible variation is avoided.

Analytical Methods

Only analytical methods described in Methods for Chemical Analysis of Water and Wastes, EPA-600/4-79-020 (U.S. Environmental Protection Agency, 1983) or Standard Methods for the Examination of Water and Wastewater, 21st edition (American Public Health Association, 2005) are recommended unless it can be demonstrated that an alternative provides the same degree of precision and accuracy. Particular analytical methods are not specified because there may be more than one suitable option for a parameter. An analytical laboratory with certification to

perform analyses of wastewater to satisfy National Pollutant Discharge Elimination System reporting requirements or have comparable certification should perform all analyses of influent and effluent samples. In the event that an analytical laboratory without the appropriate certification, such as a university research laboratory, is used, that laboratory should have an ongoing quality assurance/quality control program that is comparable to such programs required for certification. The laboratory used should have previous experience in analyzing samples with high solids concentrations, and duplicate, or preferably triplicate analyses of individual samples should be performed for all parameters.

The multiple-tube fermentation techniques described in Standard Methods for the Examination of Water and Wastewater (American Public Health Association, 2005) should be used to estimate fecal coliform, fecal streptococcus, and *Salmonella spp.* densities. For estimation of *M. avium paratuberculosis* densities, either the NADC or the Cornell Method (Stabel, 1997) is acceptable.

Hydraulic Retention Time and Temperature

Because the degree of waste stabilization will vary with HRT and actual HRT may differ from the design value, the determination of actual digester or covered lagoon influent or effluent flow rate to calculate actual HRT also is a requirement of this protocol. Because of differences among digesters, no specific flow measurement techniques are required. However, the method used, as well as the underlying rationale, should be fully described in the performance evaluation report.

In addition, digester or covered lagoon operating temperature should be determined and recorded at least during each sampling episode with the concurrent measurement of influent and effluent temperatures also being desirable. At least monthly, the accuracy of all thermometers or other temperature measuring devices should be checked using a precision thermometer with certification traceable to the National Institute of Standards and Technology (NIST). For covered anaerobic lagoons, the average daily ambient temperature over the duration of the performance evaluation also should be measured and recorded or obtained from the nearest National Oceanic and Atmospheric Administration (NOAA) weather observation station.

All reductions must be shown to be statistically significant at least at the $P<0.05$ level using the Student t test (Snedecor and Cochran, 1980.). Any suspected outliers in data sets should be tested at $P<0.05$ using Dixon's method (Snedecor and Cochran, 1980). For covered lagoons, claims of TVS and COD reductions will have to be estimated based on observed biogas production. All densities of indicator organisms and pathogens should be reported and compared statistically on a $\log_{10}$ colony-forming units (CFU) per 100 ml basis. If a reduction is claimed, it also must be statistically significant at least at $P<0.05$. When differences are found to be statistically significant, 95 percent confidence interval estimates should be reported.

Biogas Production and Utilization

Biogas Production

Total biogas production should be determined in all performance evaluations because biogas disposed of by flaring when production exceeds utilization capacity will not be accounted for when only biogas utilization is measured. Experience generally suggests that top inlet meters designed to measure corrosive gas flow are suitable. However, other types of gas flow meters, such as thermal mass flow meters, also are acceptable. Meters should be temperature and pressure compensated. Evidence of the verification of the precision and accuracy of all meters used to measure biogas production is required. All biogas production reporting should be under standard conditions (0°C, 1 atm) to allow direct comparisons of production among different systems (See Appendix B).

Biogas Composition

Biogas concentrations by volume of carbon dioxide and hydrogen sulfide should be determined at least monthly using the appropriate detection tubes for each gas. At least three replicate determinations should be made during each sampling episode. In addition, laboratory biogas analysis to determine methane, carbon dioxide, hydrogen sulfide, and ammonia content by volume should be performed at least quarterly to confirm the accuracy of the gas detection tubes. Each sample should be collected in a Tedlar™ gas collection bag and analyzed to determine

methane, carbon dioxide, hydrogen sulfide, and ammonia composition by volume using ASTM Method D 1946-90 (ASTM International, 1990) for methane and carbon dioxide, ASTM Method D 5504-01 ASTM International, 2001) for hydrogen sulfide, and EPA Method 350.1 for ammonia. Results of samples containing more than 10 percent of unidentified gases, typically nitrogen and oxygen, should be discarded due to an unacceptable degree of atmospheric contamination reflecting a poor sample collection technique. Real time electronic gas analysis also is acceptable with evidence of precision and accuracy.

Biogas Utilization

In addition to total biogas production, biogas utilization also should be measured using the same type of meter used to determine total biogas production. When biogas is used to generate electricity, the electricity generated (kWh or MJ) also should be recorded using a permanently installed utility type meter or a comparable substitute. With these data and biogas composition, the thermal efficiency of the conversion of biogas energy to electrical energy using the lower heating value (LHV) for methane should be calculated for reporting as follows:

Thermal conversion efficiency, % = [(kWh generated/unit time * 3,412) / (biogas combusted, ft^3/unit time * methane content, decimal * lower heating value of methane, Btu/ft^3)] * 100 (1a)

or

Thermal conversion efficiency, % = [(MJ generated/unit time) / (biogas combusted, m^3/unit time * methane content, decimal * lower heating value of methane, MJ/m^3)] * 100 (1b)

The lower heating value of methane, which is the heat of combustion less the heat of vaporization of the water formed as a product of combustion, should be used because condensation of any of this water with an engine-generator set is unlikely. The LHV of methane under standard conditions (0 °C, 1 atm) is 960 BTU per ft^3 (35,770 kJ per m^3) (Mark's Standard Handbook for Mechanical Engineers, 1978). However, the LHV of methane varies with temperature and pressure in accordance with the universal gas law, and the LHV of methane used to calculate thermal efficiency should be for the temperature and pressure at which biogas

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production is being measured. When reporting thermal conversion efficiency, the heating value assumed should be stated along with the time-period involved.

The engine-generator set operating hours also should measured and recorded at least monthly in order to calculate and report monthly and annual engine-generator set on-line efficiency, average output, and capacity utilization efficiency when operating as follows:

$$\textit{On-line efficiency, \% = (engine-generator set hr per unit time/ hr per unit time) * 100} \tag{2}$$

$$\textit{Average generator set output, kW = (kWh per unit time)/(engine-generator set hr per unit time)} \tag{3a}$$

or

$$\textit{Average generator set output, MJ = (MJ per unit time)/(engine-generator set hr per unit time)} \tag{3b}$$

$$\textit{Average capacity utilization efficiency, \% = (average generator set output, kW)/ (rated maximum output for biogas, kW) * 100} \tag{4a}$$

or

$$\textit{Average capacity utilization efficiency, \% = (average generator set output, MJ)/ (rated maximum output for biogas, MJ) * 100} \tag{4b}$$

When there is utilization of engine-generator water jacket or water jacket and exhaust heat for water or space heating or both, the heat energy in British thermal units (Btu) or kJ beneficially used should be measured and recorded using appropriate meters. In addition, determination of the heat energy utilized for digester heating, when applicable, is recommended.

Data Collection

All meters used to measure biogas production and utilization, electricity generated, engine-generator set hours, and waste heat beneficially utilized should be calibrated or recalibrated, if previously used, by the manufacturer prior to the beginning of each performance evaluation. In addition, each meter should have a manually nonresettable totalizer to avoid accidental data loss, and all meter readings should be recorded at least during every sampling episode with the date

and time of the meter reading noted. In addition, a copy of the digester operator records should be obtained monthly.

When biogas is being used to fuel an internal combustion engine or micro-turbine to generate electricity with an interconnection with a local electric utility, the ASERTTI Distributed Generation Combined Heat and Power Case Study Protocol for the evaluation of biogas utilization should be followed. By following this protocol, data collected can be transmitted to a national database at the National Renewable Energy Laboratory, which is strongly encouraged. The ASERTTI case study protocol can be obtained at www.dgdata.org.

<u>Greenhouse Gas Emissions Reductions</u>

Each report should include estimates of the reductions in methane and carbon dioxide, and when appropriate, emissions resulting from the use of anaerobic digestion for the production and utilization of manurial biogas. Estimates of reductions in methane emissions should not be based on methane production. Rather, they should be based on estimated emissions from conventional manure management practices in place (*e.g.,* storage tanks or ponds or lagoons) without anaerobic digestion using the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004 (U.S. Environmental Protection Agency, 2006) methodologies. These emission estimates (www.epa.gov/climatechange/emissions/downloads06/06Agriculture.pdf) were developed by the Intergovernmental Panel on Climate Change and presented in Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (International Panel on Climate Change, 2000). For new livestock operations, estimated methane emissions without anaerobic digestion should be based on those conventional waste management practices that would have been employed without anaerobic digestion. For example, scraped dairy cattle manure would be stored in a tank or earthen pond, not a conventional anaerobic lagoon. Because methane emissions from manure storage structures are substantially lower than those from conventional anaerobic lagoons, an estimate of the reduction in methane emissions assuming that a conventional anaerobic lagoon would have been used to store scraped dairy cattle manure are inappropriate. EPA has prepared a performance standard (accounting methodology) for the Climate Leaders Program to calculate greenhouse gas reductions from livestock waste projects.

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This methodology should be used to calculate and report greenhouse gas reductions under this protocol (www.epa.gov/climateleaders/docs/ClimateLeaders_DraftManureOffsetProtocol.pdf).

Estimates of carbon dioxide emissions avoided by reducing the demand for electricity generated from fossil fuels should be calculated using EPA's Power Profiler (www.epa.gov/cleanenergy/powpro/screen1.html). This tool provides greenhouse gas emission estimates (lbs/MWh) from conventional fossil fuel based on geographical location and fuel mix used.   Emissions data for the Power Profiler is supplied from EPA's Emissions & Generation Resource Integrated Database, or E-Grid (www.epa.gov/cleanenergy/egrid/index.htm).

Reporting

If co-digestion of livestock manure and another waste or feedstock is being practiced, reporting biogas and methane production and electricity generated on a per head basis is inappropriate. This practice, which has been employed in the past, is misleading and inaccurate. When the performance of systems co-digesting manure and another waste or feedstock is being evaluated, biogas and methane production and electricity generated should be reported as a function of the average daily loading of TVS and COD over the duration of the study. In addition, the average daily loadings of manure and other waste TVS and COD should be reported concurrently.

Economic Analysis

It is generally accepted that the anaerobic stabilization of livestock manures under controlled conditions can significantly reduce the potential impacts of these wastes on air and water quality with the recovery of a substantial amount of usable energy. However, the decision to construct and operate manurial biogas systems depends ultimately on the anticipated ability to at least recover any internally derived capital investment with a reasonable rate of return, and service any debt financing over the life of the system. Otherwise, other investment opportunities become more attractive unless the need for environmental quality benefits, such as odor control, justify the net cost of system operation. Thus, all manurial biogas system performance evaluations should include a financial analysis performed in accordance with the general principles of engineering economics as outlined by Grant *et al.* (1976) and others.

In the past, several approaches have been used for assessing the economic attractiveness of these systems. One is the simple determination of the time to recover the internally derived and borrowed capital investment from the revenue generated. This payback period approach has the merit of simplicity but does not consider the time value of money. The present worth or net present value is another approach in which the value of future revenue is discounted to present worth and compared to the required capital investment. The problem with this approach is the result obtained is dependent on the necessary assumption of a single discount rate over the life of the system. In addition, it provides no guidance with respect to annual net income or loss from the biogas production and utilization effort. Therefore, this protocol requires a cash flow approach described below in which total annual cost and annual revenue are calculated and compared to determine the net income or loss being realized annually. However, results of payback period and present worth calculations also can be presented in performance evaluation reports if desired.

General Approach

Economic analysis of manurial biogas production and utilization systems should be performed from the perspective that the system is an independent enterprise with annual net income or loss for the system being the single metric used to characterize financial viability. When part of a livestock operation, the biogas energy used by other parts of the operation is treated as a source of income for the biogas enterprise along with payments received for any biogas energy sold to a third party.

Boundary Conditions

Because manurial biogas production and utilization is an optional component of manure management systems, the delineation of appropriate boundary conditions that exclude costs and revenue sources that are not dependent on the biogas enterprise is critical for cost analysis credibility. For example, costs associated with manure storage following anaerobic digestion should not be included as components of either biogas system capital or annual operation and maintenance costs, because biogas production and utilization does not require subsequent manure storage. Rather, they are costs of an independent decision to store manure to minimize

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impacts on environmental quality associated with current land application practices or to maximize manure value as a source of plant nutrients for crop production. Another example of an inappropriate cost component would be inclusion of the cost of a pump to transfer manure to an anaerobic digester when a pump is required without digestion to transfer manure to a storage structure. However, a second pump would qualify if the anaerobic digester effluent cannot be transferred to the storage structure by gravity.

With respect to complementary operations such as separation of coarse solids from anaerobically digested dairy manure, there has been debate about the treatment of costs and revenue. Commonly, the capital and operating costs of solids separation have been considered as part of the biogas production and utilization system total cost with on-site use of the separated solids as bedding or sale as bedding or a soil amendment or mulch material considered a source of revenue. However, this activity does not meet the test of being necessary for biogas production and utilization because separation of coarse solids from dairy manure can be accomplished without anaerobic digestion as a prerequisite. Thus, solids separation should be considered as a separate enterprise in this context with the caveat that any reduction in the final stabilization cost for the solids used on-site or sold does represent revenue to the biogas enterprise.

Similarly, the cost of separating coarse solids from dairy manure entering a covered lagoon should not be considered as part of the cost of biogas production and utilization, because removal of these solids is necessary for the satisfactory performance of conventional anaerobic lagoons, and the cost is the same. In addition, the revenue derived from the separated solids with and without biogas production will be the same. After considering this example, the rationale for excluding consideration of all costs and revenue associated with complementary operations in the financial analysis of manurial biogas should be apparent. However, solids separation could be analyzed financially as a discrete enterprise with the results reported separately and then combined with the results of the economic analysis of biogas production and utilization if desired.

It is recognized in this protocol that variation among biogas production and utilization systems and site-specific conditions may require specification of different boundary conditions for financial analysis, and has to be based on best professional judgment. When the rationale for the

boundary conditions specified is not entirely clear, a brief explanation of the underlying logic should be included with the results of the economic analysis. In all cases, the report presenting the results of the performance evaluation should include a schematic that identifies the boundary conditions assumed for the economic analysis.

Methodology

Annual Capital Cost—The first step in determining annual net income or loss from manurial biogas production should be the calculation of the annual capital cost of the system using the annual cash flow approach. To do so, three initial assumptions are necessary. The first is that the recovery of the internally derived capital invested and the retirement of debt financing will occur by a uniform series of annual payments over the useful life of the system, or a shorter period if desired. Thus, a second assumption, an estimate of the useful life of the system, also is necessary. Although an assumed value of 20 years generally is standard for structural components, it clearly is unrealistically long for flexible covers, which generally have an assumed useful life of about 10 years, and mechanical equipment, which usually has an assumed useful life of seven years. However, all system components can be considered to have a useful life of 20 years if reconditioning or replacement costs for components having a useful life of less than 20 years are considered to be part of operation and maintenance costs. In the interest of simplicity and standardization, this third assumption also is recommended. However, a more detailed approach also will be acceptable if reconditioning and replacement costs are not included in the estimate of annual operation and maintenance cost, as will the less conservative assumption of capital recovery over 10 instead of 20 years.

Generally, manurial biogas systems are financed with a combination of internally derived and borrowed capital, and in some instances also with cost-sharing assistance, which may be in the form of a grant or a below market interest rate loan. One of the objectives of this protocol is to establish a single database that allows the comparison of different types of manurial biogas production and utilization systems and of similar systems in different geographical locations. Therefore, all determinations of the annual capital cost individual systems should be based on the turnkey cost and not the net cost to the owner.

In calculating the annual capital cost of the system, it is recommended, again for simplicity, that the rate of interest being paid for borrowed capital is a reasonable rate of return to the internally derived capital invested. Another merit of this approach is that a request for information that the system owner may consider confidential business information is avoided. Therefore, the annual capital cost is calculated simply by multiplying the turnkey cost of the system by the capital recovery factor for a uniform series of payments over 20 years, or 10 years if desired, at the interest rate being paid for borrowed capital.

Annual Operation and Maintenance Cost—Because of a paucity of supporting information, one of the more uncertain aspects of the economic analysis of manurial biogas systems has been the ability to realistically estimate annual operation and maintenance costs. This lack of information is due, at least in part, to the inability to have system owners maintain a detailed record of operation and maintenance costs during previous performance evaluations. However, it is unrealistic to assume that the operation and maintenance cost incurred during a 12-month performance evaluation will be representative of the average annual operation and maintenance cost given that maintenance costs will tend to increase with the age of the system and most performance evaluations will be of relatively new systems. Therefore, the standard assumption that the average annual operation and maintenance cost will be three percent of the turnkey cost should be used until better information becomes available. However, management and labor requirements for routine system operation should be recorded and reported as part of all performance evaluations as part of an effort to delineate more clearly the cost of biogas system operation and maintenance.

Other Annual Costs— The construction of a manurial biogas system may increase the assessed value of a livestock operation and therefore increase annual real estate taxes. It also may increase the annual cost of insurance on structures and equipment and possibly the cost of liability insurance. In addition, other costs may increase plus new costs may occur. For example, the cost of manure collection may increase if collection frequency increases. Also, an operating permit with an annual fee may be required. The magnitudes of these increases should be determined and added to the estimated annual capital and operation and maintenance costs to determine the total annual cost of the system. Similarly, other annual costs in addition to

20

operation and maintenance costs (*e.g.,* insurance, real estate taxes, salaries, fringe benefits, transportation, *etc.*) will be incurred for centralized systems. All of these costs should be identified and included in the economic analyses of manurial biogas systems when possible, or their absence should be noted.

Annual Revenue—For most manurial biogas systems, electricity generated will be the primary, if not sole source of revenue. For systems with sell all/buy all utility contracts, the annual revenue generated by the system simply will be the sum of payments received from the utility annually. The estimation of annual revenue from generation of electricity for operations with surplus sale or net metering utility contracts is more difficult due to the problem of placing a value of the biogas generated electricity being used on site. Because of the way rate schedules for electricity generally are structured, the average cost per kWh decreases as the amount of electricity purchased increases. Therefore, reducing the amount of electricity purchased can increase its unit cost. In addition, on-site use of biogas generated electricity may either increase or decrease demand charges and may result in the addition of a stand-by charge. Assuming that the average value per kWh of biogas electricity used on-site is equal to the average cost per kWh of electricity purchased from the utility, if there was no on-site use of biogas generated electricity, may result in either an over or under estimate of the annual revenue from on-site biogas generated electricity use. The recommended approach for dealing with this issue is to compare the total cost of electricity purchased from the local utility for the 12 months prior to start-up of the manurial biogas system with the total cost for the 12 months of the performance evaluation with the difference being the revenue generated by on-site use. If, however, the livestock operation is a new operation, or there were significant changes such as expansion when biogas production began, the only alternative is to develop an estimate of what the cost of electricity would have been without biogas production. This should be done from the record of on-site biogas electricity consumption and purchases from the local utility for the 12 months of the performance evaluation. In all cases, the validity of the estimate produced should be confirmed by evidence that the period of the performance assessment is reasonably typical with respect to ambient temperature.

For combined heat and power systems where engine-generator set waste heat being recovered for beneficial use, the revenue being derived from waste heat utilization should be calculated based on the cost per unit of energy for the conventional fuel being replaced and the waste heat energy being utilized. The same approach should be used when estimated revenue derived from only using biogas as a boiler or furnace fuel. Because costs of the conventional fuels most likely to be replaced, liquefied petroleum gas or No. 2 fuel oil, vary seasonally, the impact of seasonal variation in biogas use and value should be incorporated in revenue estimates.

Net Income—After calculations of total annual cost and annual revenue are made, net income from the biogas enterprise before income taxes can be quantified. An attempt to estimate net income after income taxes should not be made because income from the biogas system only will be a component of total income from the livestock operation, which may vary significantly over the life of the biogas system. In addition, the confidential business information issue will be avoided.

Report Format

Reports presenting results of manurial biogas system performance evaluations should contain the following sections:

- Summary and Conclusions—A brief overview of the performance evaluation and presentation of the major findings.

- Introduction— Descriptions of the location of the performance evaluation and the biogas system evaluated followed by the objectives of the evaluation.

- Methods and Materials—A description of methods and materials employed in the performance evaluation.

- Results—Summaries of the results obtained.

- Discussion—A discussion of the results obtained especially with respect to similarities to and differences from previously reported results.

- References—A list of literature cited following the format used in this document.

- Appendices—
  - A copy of the QA/QC plan for the laboratory that performed digester influent and effluent sample analyses,

- A record of tests of the accuracies of meters and temperature measuring devices used,
- All data collected in tabular form, and
- Technical specifications (meta data) for the DG/CHP portion of the system.

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Appendix A

Material Balances

A material balance (or inventory) is a simple accounting of any material in a system, which may be a single unit, a collection of units, or an entire system and generally may be stated as:

$$
\begin{aligned}
&\textit{Input (enters through the system boundary)} + \\
&\textit{Generation (produced within the system)} - \\
&\textit{Output (leaves through the system boundary)} - \qquad\qquad\text{(A-1)} \\
&\textit{Consumption (consumed within the system)} = \\
&\textit{Accumulation (buildup within the system boundary)}
\end{aligned}
$$

If there is no generation or consumption within the system boundary, as is the case with fixed solids (FS) and total phosphorus (TP) in an anaerobic digestion reactor, Equation A-1 reduces to:

$$
\begin{aligned}
&\textit{Input (enters through the system boundary)} - \\
&\textit{Output (leaves through the system boundary)} = \qquad\qquad\text{(A-2)} \\
&\textit{Accumulation (buildup within the system boundary)}
\end{aligned}
$$

In the analysis of the performance of livestock and other waste treatment or stabilization processes, it generally assumed that no accumulation of any substance due to settling is occurring if the input of FS, and preferably also TP, is equal to the output. Therefore, any difference between input and output must be due to generation or consumption and Equation A-1 reduces to:

$$
\begin{aligned}
&\textit{Input (enters through the system boundary)} + \\
&\textit{Generation (produced within the system)} = \qquad\qquad\text{(A-3)} \\
&\textit{Output (leaves through the system boundary)} - \\
&\textit{Consumption (consumed within the system)} +
\end{aligned}
$$

If generation is zero or negligible in comparison to consumption, Equation A-3 reduces to:

$$
\begin{aligned}
&\textit{Input (enters through the system boundary)} - \\
&\textit{Output (leaves through the system boundary)} = \qquad\qquad\text{(A-4)} \\
&\textit{Consumption (consumed within the system)}
\end{aligned}
$$

and treatment or stabilization efficiency is calculated as follows:

$$
\begin{aligned}
&\textit{Treatment or stabilization efficiency, \% =} \qquad\qquad\text{(A-5)} \\
&\textit{(Consumption/Input) * 100}
\end{aligned}
$$

The basis for material balances for continuous steady-state processes such as anaerobic digestion usually is mass flow rates (*e.g.,* kg per hr). However, material balances to estimate treatment or stabilization efficiency also can be constructed using concentrations (*e.g.,* mg per L) when volumetric flow rates (*e.g.,* L per hr) are equal. Although, there is some reduction in volume

during anaerobic digestion due to the saturation of the biogas leaving the reactor with water vapor, the reduction in volume is negligible and can be ignored.

For estimating chemical oxygen demand (COD) reduction in covered lagoons based on methane production under standard conditions, the relationship is:

$$COD_{reduction}, \text{ lb/unit time} = (\text{Methane production, } ft^3 \text{ } CH_4 \text{ /unit time})/ \qquad \text{(A-6a)}$$
$$(5.60 \text{ } ft^3 \text{ } CH_4/\text{lb } COD_{destroyed})$$

or

$$COD_{reduction}, \text{ kg/unit time} = (\text{Methane production, } m^3 \text{ } CH_4 \text{ /unit time})/ \qquad \text{(A-6b)}$$
$$(0.3496 \text{ } m^3 \text{ } CH_4/\text{kg } COD_{destroyed}$$

For non standard conditions, the universal gas equation should be used to determine the volume occupied by one mole of methane and the methane equivalent of COD converted under anaerobic conditions assuming 64 g COD per mole of methane.

Appendix B

Biogas Production

To determine biogas production under digester operating conditions from COD destruction based on the stoichiometrically based estimate that 5.60 ft^3 of methane are produced per lb of COD destroyed (0.3496 m^3 per kg COD destroyed) under standard conditions (0°C and 1 atm) or correct non temperature or pressure compensated biogas production measurements to standard conditions, the following relationship (the general gas law) should be used.

$$V_2 = V_1 * (T_2/T_1) * (P_1/P_2) \tag{B-1}$$

Where: V_1 = gas volume (m^3) at temperature T_1 (°K) and pressure P_1 (mm Hg)
   V_2 = gas volume (m^3) at temperature T_2 (°K) and pressure P_2 (mm Hg)